Method for Computing Motor Vehicle Crash Energy Based on Detailed Crush Data and Stiffness Values

by

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Abstract

An experimental methodology is proposed to compute the crash energy of motor vehicles based on detailed deformation data and structural stiffness values. The procedure uses data produced by emerging 3D data capture methods to accurately and completely describe the crash deformation of a subject vehicle by comparing it to the undeformed exemplar data. Unlike the current inputs for traditional crash energy calculations, this method allows for crush measurements to be analyzed for multiple heights and positions across the damage plane of the vehicle. In conjunction, high-resolution load cell barrier data from NHTSA's frontal NCAP tests were used to develop a 3D stiffness matrix for the vehicle front structure. The crush data and stiffness matrix were then used to calculate the deformation energy by each load cell region and the Equivalent Barrier Speed for the vehicle in question. This work takes the initial steps to begin validating the new approach by using the public domain finite element models produced by the George Washington University National Crash Analysis Center (NCAC). The FE model is run under both NCAP Frontal and IIHS 40% Overlap crash configurations and the resulting deformed vehicles are used as inputs for the paper's methodology. Although the preliminary results are promising, additional development and analysis is needed before it can be widely adopted.

Preface

I would like to express my gratitude to Impact Research, LLC and BMW of North America, LLC for providing me with the funding and access to the equipment and information used to conduct and complete this work. I would also like to thank Dr. George Bahouth and Dr. Kennerly Digges for their guidance and support during my research. In addition, I would also like to thank Dr. Somnath Ghosh and Dr. Thao (Vicky) Nguyen for serving on my advisory committee, as well as for their guidance in completing this work. I want to thank Mike Bernard for the constant support throughout the research process.

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Table of Contents

List of Tables

List of Figures

List of Plates

1. Introduction

According to the National Highway Traffic Safety Administration (NHTSA), “there were an estimated 5,615,000 police-reported traffic crashes in which 33,561 people were killed and 2,362,000 people were injured” within the United States in 2012 alone (1). In a continued effort to reduce these numbers, the automotive industry has maintained a large emphasis on the study and analysis of motor-vehicle crashes. These findings are then used in the development and improvement of vehicle safety systems.

1.1 Background and Significance

Although it is unclear exactly when the concept of automotive safety emerged, one might suggest it started in 1869 after the first recorded motor-vehicle fatality world-wide occurred in Ireland (2). The automotive industry has come a long way since then, but the importance of occupant safety has remained strong. As a result over the years, many new vehicle design changes and technological advances have been introduced with the objective of mitigating crash injuries and decreasing fatalities.

To assist in the development of automotive safety technology, motor-vehicle crash analysis and reconstruction methods have been used to investigate and understand the causes, events, and results of automotive collisions. The information determined through these practices has many widespread applications including the testing and evaluation of safety equipment, the improvement of future vehicle designs, the development of both passive and active automotive safety features, the development and modification of roadway configurations, and in settling legal cases and disputes (e.g. to assign legal fault for the collision or prove a vehicle defect).

In the 1930’s, a few Universities and select vehicle manufacturers began the practice of conducting staged automotive crash tests in an effort to better understand the dynamics of motor-vehicle collisions. These tests served two main functions: 1) they allowed researchers to study the effectiveness of new safety technology, and 2) they became very useful tools to define the crash characteristics and to quantify the severity of real-world crashes by serving as known comparisons. Early tests were conducted with cadavers, living volunteers or animals as the occupants until the 1950's when crash dummies were developed (3).

In 1970, the U.S. Department of Transportation established the National Highway Traffic Safety Administration (NHTSA) which has since helped to set and enforce motor-vehicle safety performance standards, through its extensive crash testing. NHTSA's New Car Assessment Program (NCAP) is used to evaluate the crashworthiness of new automobiles by conducting a series of standardized crash tests designed to simulate common real-world crash configurations. After testing the vehicle in frontal, side and rollover crash configurations, a set of safety ratings is calculated and published.

Unlike staged crash tests, most vehicle collisions that occur in the field typically have very limited information that is directly known or available regarding the crash conditions and driving input factors from the time preceding the crash till the vehicle(s) have reached their final resting positions. Thus significant research has been done to develop scientific and engineering methods which use the evidence measured/collected from the accident scene, the vehicle damage and the occupant injuries to extrapolate important crash characteristics describing the accident conditions, the impact configuration(s) and crash severity.

In order to accurately reconstruct an automotive crash, one of the most valuable pieces of evidence that can be collected/measured is the deformation to the vehicle(s) involved. Based on the location and extent of the residual crush, a number of significant crash characteristics can be determined, including: the number of impacts to the vehicle(s), the relative position that the vehicle(s) were in at the time of impact, the angle of the primary direction of force (PDOF) and the understanding of which parts and structures of the vehicle were engaged (or not engaged) during the crash. With the use of relevant crash test data to provide vehicle stiffness values, the vehicle crush measurements can be used to calculate the approximate amount of energy absorbed by the vehicle during deformation, which in turn can be used to estimate the vehicle's change in velocity (delta-V) and its Equivalent Barrier Speed (EBS) during the crash.

The current industry standard determines the deformation profile through a series of crush measurements using the offset method. The method is based on defining a reference line, which is a known distance from an undeformed part of the vehicle, and then taking individual measurements (typically evenly spaced) across the deformed region from the surface on the post-crash vehicle back to that line. The individual measurements are typically done using a tape measure, measuring poles or grids. Since the methods define the deformation profile with only a small set of estimated measurements, the accuracy of the resulting crash energy calculations is limited.

In recent years, technological advancements have been made in the development of three-dimensional (3D) geometrical data capture techniques. These 3D scanners can allow crash investigators to gather significantly more measurements in a much shorter period of time and with potentially greater accuracy. The scanners also allow for the digitalization of the exterior of the crash vehicle, letting investigators reference the geometry at a later point in time (potentially after the vehicle has been repaired or destroyed).

Now that 3D scanners are becoming cheaper, faster, more accurate, more portable and able to capture data with higher resolution they are beginning to be used in the crash reconstruction process. The issue is that there are no crash energy calculation methods currently in place capable of handling the amount of crush measurement data recorded by the scanners and thus the benefit of the increased number and resolution of points is lost.

The current industry standard for crash energy calculation is based on an assumed linear relationship with vehicle crush. It determines the stiffness relationship by deriving two coefficients, a slope and y-intercept, from relevant crash test data. The slope represents the crush-energy ratio and the y-intercept represents the adjustment for dissipated elastic energy. The method assumes that stiffness is uniform across both the damage area's height and width, which proves to be an issue in more complicated crash configurations (eg. override, off-set frontal, etc.).

In 2010, NHTSA began using high-resolution load cell barriers in some of their full frontal NCAP tests. This development opens the door for the derivation of more detailed stiffness values that vary along the height, width and depth of a vehicle's front structure. An understanding of the amount of crush and associated deformation energy absorbed by specific parts and structures of the vehicle and in specific crash configurations is considered extremely valuable to automotive manufactures. The data can be used for the material and structural design improvements to make future vehicle designs both safer and more efficient.

1.2 Research Objectives and Approach

This thesis presents a method for computing motor vehicle crash energy based on detailed crush data and stiffness values by incorporating emerging three-dimensional data capturing techniques. The motivation is based on the potential of overcoming some of the limitations with current methods by defining the crush more completely and using specific corresponding stiffness values to determine vehicle crash energy.

The method includes the following three goals:

- The use of three-dimensional data capture methods to measure geometry of crash deformed vehicles in an effort to create a 3D characterization of deformation.

- The collection and processing of vehicle crash test and simulation data to generate stiffness coefficients corresponding to the case vehicle(s).
- And finally the use of the characterization of deformation and the stiffness coefficients to calculate a candidate vehicle's crash energy studied. As a result, the Equivalent Barrier Speeds (EBS) can be determined.

1.3 Research Scope

For the development and use of the three-dimensional characterization of deformation, crashes were limited to those in which the outer structure on the deformed vehicle can accurately be compared to the corresponding exemplar vehicle. In addition, the crash configurations used were limited to those where the primary direction of force is either 12, 3, 6, or 9 o'clock.

For the subsequent steps of the method, the derivation of stiffness values and the calculation of crash energy, the crash configurations used were further limited to only include frontal 12 o'clock crashes. This was done for the use of NHTSA Full Frontal NCAP crash test data to determine the frontal stiffness values.

1.4 Limitations

The following limitations existed:

- 3D data capture methods used were limited by accessible equipment/technology.
- Access to scan a NHTSA NCAP test was not granted. Thus it was necessary to use an FEA model for the development and testing of the crash energy calculation method.
- There are a limited number of vehicles that have been tested by NHTSA's Full Frontal NCAP test with a high-resolution barrier, that have also been tested by IIHS' 40% overlap crash test configuration.

1.5 Thesis Outline

This thesis consists of six chapters including necessary background, significance, objectives and approach of the research in Chapter 1. Chapter 2 provides a summary of past and present research findings related to damage based vehicle crash analysis and the characterization of vehicle deformation. Chapter 3 details the framework and methodology for the characterization of deformation, the derivation of detailed stiffness values and the calculation of crash energy.

A description of the process in which the raw data is input into the method and the steps it undergoes to calculate crash energy is presented in Chapter 4. Chapter 5 presents the preliminary method results of processing IIHS' 40% overlap crash configuration based on the stiffness values from NHTSA's Full Frontal NCAP Test. Lastly, Chapter 6 provides conclusions based on the work done as well as recommendations for future research.

A visualization of the developed method's inputs and outputs can be found in Appendix 2.

2. Literature Review

This chapter contains a summary of past and present research and findings relating to damage based vehicle crash analysis and the characterization of deformation. This collection of research serves as the basis and motivation for the crash energy calculation method proposed.

2.1 Damage Based Accident Reconstruction

In the early stages of automotive crash analysis, the crash severity of a collision in the field was approximated using a series of crash tests under set known/determined conditions (eg. vehicle type(s), impact position(s), impact angle(s), etc.) while varying other unknown conditions (eg. impact velocity). The crash test (or average of multiple tests) that had the closest match to the vehicle deformation(s) and the final resting position(s) seen in the field was used for defining the severity. Although this method can be quite accurate, it is an extremely expensive and time consuming process that cannot always be done.

Instead of conducting a set of crash tests for each accident case, the next best alternative is to compare the deformation of the case vehicle(s) to the results from published crash tests (4). The issue with this is that real-world accidents occur in such a wide variety of conditions, severities and outcomes that the "damage profiles of accident vehicles will rarely match those of test vehicles" and thus "it is in general necessary to have a model relating energy to crush" (4). This model would allow for the use of crash testing under generalized conditions, yet still allowing for more complex configurations to be estimated.

In 1968, Emori (5) proposed a method that was designed to do just that. It was considered one of the first notable publications on the topic of damage based accident reconstruction. In the *Analytical Approach to Automobile Collisions*, Emori analyzed experimental results to "suggest that frontal and rear-end automobile collision processes may be simulated by a simple model with a mass, which represents the vehicle mass, and a spring, which represents the resisting force due to crushing of the vehicle structure" (5). This was the first time a method was proposed that allowed crash energy calculations to be done, with reasonable accuracy, without the use of specific crash tests.

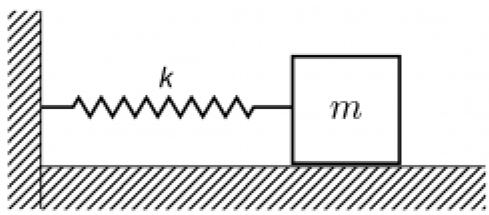


Figure 1 – Simple Mass-Spring System (6)

Emori's paper (5) also indicated that the crush dynamics seen for frontal collisions was different than those in rear-end collisions. The research suggested that the fronts of vehicles could be modeled with a "one-way linear" spring versus the rear-end model's "spring is almost rigid plastic" (5). Given these models, Emori proposed that the amount of crush on the front of a vehicle should be directly proportional to the impact velocity, where the impact velocity is equal to 1.1 mph per inch of residual crush. It should be noted that this calculation assumes one value is used to describe the vehicle's residual crush. The residual crush is defined as the non-reversible deformation that can be seen post-crash, once the elastic portion of the deformation has been restored.

The next advance came in 1972 when both Campbell (7) and Mason and Whitcomb (8) expanded upon Emori's research and independently published reports which proposed a "linear relationship between residual crush and frontal fixed rigid barrier speed" in the following form:

$$Barrier\ Impact\ Velocity = b_0 + b_1(Residual\ Crush) \qquad \text{Eq. (1)}$$

Both groups went on to present a set of b_0 and b_1 coefficients, based on data from General Motors crash tests, which could be used as rough approximations. Mason and

Whitcomb also suggested that this calculation of velocity was equal to roughly half of the closing velocity in a car-to-car impact in which the cars are of reasonable size and type (8).

Based on Eq. (1), Campbell later determined that the “simplest model for the vehicle front structure which will reproduce the linear relationship observed between impact speed and residual crush for the barrier test is a linear force-deflection characteristic” (9). Thus concluding that:

$$Force/_{width} = A + B\ (Residual\ Crush) \qquad \text{Eq. (2)}$$

Campbell further proposed that “the energy absorbed (work done) can be computed by integrating this force over the distance crushed, to give energy absorbed per unit width, and then integrating over the width of the vehicle” (9).

$$Crush\ Energy = \int\int (A + BC)\,dC\,dw \qquad \text{Eq. (3)}$$

where C is the crush depth and w is the width of the deformation.

In his model, he assumed that the linear force-deflection does not vary across the width of the vehicle and that the damage is uniform vertically. The model also introduces the idea that the vehicle’s deformation pattern should be represented by more than one crush value. Campbell derived a set of crush pattern equations for angle barrier and offset barrier impacts.

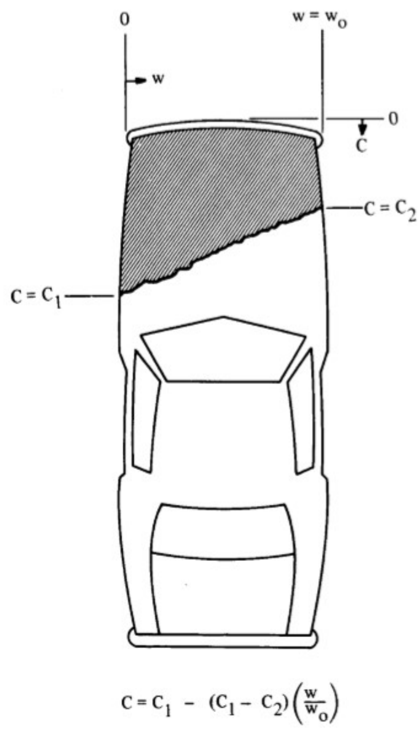


Figure 2 - Campbell's Damage Pattern for Angle Barrier Impacts (7)

Campbell also introduced the term “Equivalent Barrier Speed (EBS)” and proceeded to define it as the “vehicle velocity at which the kinetic energy of the vehicle would equal the energy which was absorbed in plastic deformation” (9). EBS is often used as the primary indicator of collision severity and can be calculated from the crush energy using the following equation:

$$Crush\ Energy = \frac{1}{2} * (Vehicle\ Mass) * (EBS)^2 \qquad \text{Eq. (4)}$$

Shortly after the publication of Campbell’s new method, NHTSA provided funding to the Calspan Corporation for the development of a program called CRASH (Calspan Reconstruction of Accident Speeds on the Highway) (10). CRASH was originally as an assist to NHTSA’s SMAC (Simulation Model of Automobile Collisions) users to estimate the vehicle impact speeds. It quickly ended up becoming a stand-alone software and the industry standard for the estimation of crash delta-V (and thus the severity of the collision). “The program had two separate and independent methods, trajectory analysis and damage analysis" (10). The trajectory analysis, which is not discussed further in this research, uses the principle of conservation of linear momentum and requires detailed crash scene measurements of the rest positions, skid marks, coefficient of friction, and point of collision.

The damage-based method was based on Campbell's observation of a linear relationship between impact speed and residual crush, Eq. (2). The method was designed to accept 2, 4, or 6 evenly spaced crush measurements in conjunction with stiffness coefficients (A and B) derived from crash tests. The program was revisited and updated many times to improve upon the derivation of the stiffness values until it eventually became CRASH3 (McHenry Software, USA).

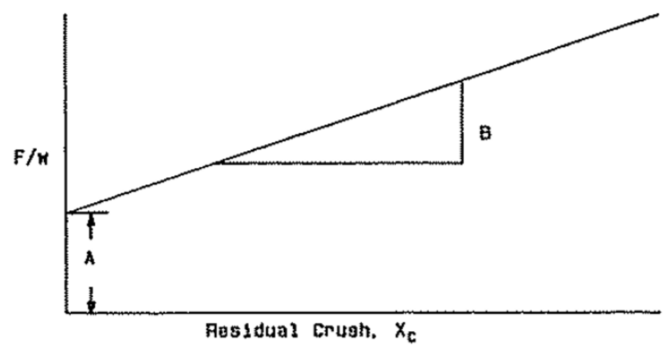


Figure 3 - The Campbell/CRASH3 Model of Vehicle Structural Response (4)

Since the release of CRASH3, many studies have been done on its accuracy when estimating delta-V, which is defined as the change in velocity that the vehicle undergoes during the time from impact to separation. In 1982, Smith and Noga (11) used CRASH3 to analyze 27 vehicle crashes and compared the results with data from available crash tests. The study found that, on average, delta-V was underestimated by approximately 10%. In 1986, Strother et al. (4) published a report that argued that the accident reconstruction methods based on deformation energy are the most useful and accurate. Yet, they also identified some issues with the CRASH3 methodology. They found that the use of "published stiffness coefficients for vehicle size categories are generally not appropriate" due to large errors (4). Instead, they propose the use of applying the results of relevant staged crash tests, crashes done in a laboratory setting in which specific vehicles are used and the crash conditions are designed to best match a crash of interest. The report also argued that under some conditions the linear force-deflection assumption is not valid and that the vehicle may become stiffer as an increased force is exerted.

In 1990, as a result of some of the CRASH3 criticism, the NHTSA Vehicle Research and Test Center "used repeated test techniques on later model year cars" (12) which showed that significant changes have been made to the structure and materials used in the vehicle body and thus the damage based algorithm needed to be changed (13). The new crush-energy relationship, as seen below in Figure 4, was implemented in the reformulated version of CRASH3, called SMASH, and later in the user-friendly version, called WinSMASH (14). The variable E_A is the amount of energy absorbed by the vehicle structure, w represents the width of the damaged region, and d_0 and d_1 are the stiffness coefficients. This model assumes the deformation follows a linear force-deformation pattern, i.e. a linear stiffness spring.

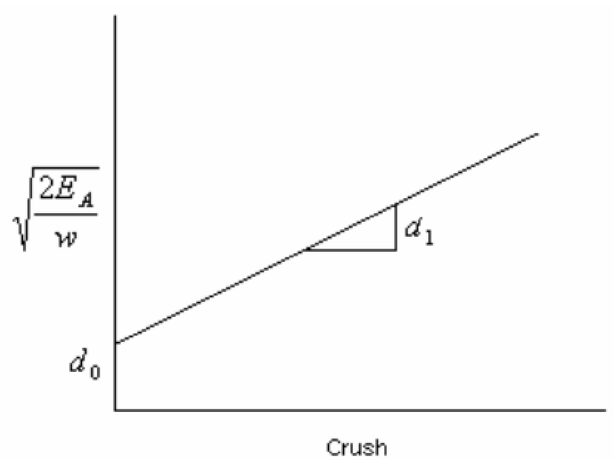


Figure 4 - The WinSMASH algorithm for damage based analysis. (14)

Even though the WinSMASH program has come a long way since its start, the code is still known to have some issues. One clear issue with the CRASH3 method of calculating crash energy and delta-V is for frontal offset crash configurations. A report at the Enhanced Safety of

Vehicles in 1996 analyzed 41 crash tests using the frontal offset configuration and reported "that CRASH3 produced a delta-V estimate that was approximately 33% less than the impact speed of the collision" (15). In 1998, Stucki and Fessahaie used WinSMASH to analyze collisions with varying degrees of offset and found that "decreased vehicle frontal overlap led to greater delta-V underestimates" (16).

Many of the crash energy and delta-V calculation errors seen in WinSMASH are due to basic assumptions that are made in the methodology. The inaccuracy of the offset crash configuration delta-V estimate is mainly due to the inability of WinSMASH's six crush values to describe the deformation area and the error in assuming uniform linear stiffness across the vehicle. Other errors seen in published data sets include issues based on the inability for the crush profile to be accurately described with 6 crush measurements, non-uniform stiffness across the impacted region of the vehicle, non-uniform deformation in the vertical direction due to underride or override, and the use of more detailed stiffness parameters.

A study published by Wang and Gabler in 2007, looked into the accuracy of both the crush values and the stiffness values that are used in the WinSMASH crash reconstruction code (17). The research showed that small miscalculations in the residual crush measurements (through physical measurements) can lead to significant errors in the delta-V calculation. On the other hand, the paper did support the use of crash test accelerometers to determine maximum crush by taking the double integral. These claims were proven by comparing the data to results from high-speed video analysis.

2.2 Characterization of Deformation

In order to run the CRASH3 program, users are asked to input a set of 2, 4 or 6 points to describe the deformation (18). The standard method to determine these values is through a series of crush measurements using the offset method. The method is based on defining a reference line, which is a known distance from an undeformed part of the vehicle, and then taking individual measurements (typically evenly spaced) across the deformed region from the surface on the post-crash vehicle back to that line. The individual measurements are typically done using a tape measure, measuring poles or grids. Plate 1 shows a crash investigator using the offset method to measure the vehicle deformation.

Plate 1 - Picture of Crash Investigator Measuring Deformation Values (19)

Figure 5 shows an example of six crush measurements, C1-C6, being used to describe the deformation profile for a full frontal crash. L represents the length of the damaged region. In this example, the damage covers the entire front of the vehicle, thus L/2 is both the centerline of the damage and the vehicle. Across that region, C1-C6 are the measurements of crush from the original undeformed location to the deformed location.

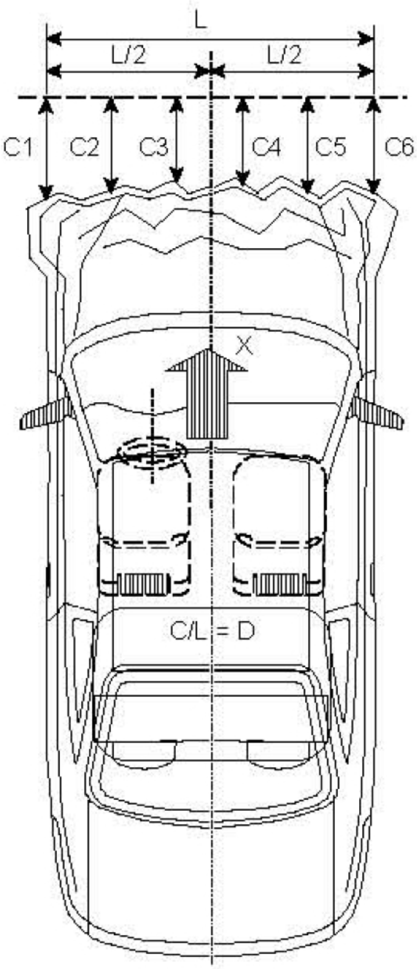


Figure 5 - CRASH3 Crush Values (C1-C6) (20)

In an effort to understand the accuracy of the offset method when using different materials (plastic, tape, plywood, and string), a study was published in 1987 where “vehicle damage resulting from collisions with a known speed is measured with techniques of increasing sophistication and the results are compared” (21). They concluded that all the manual offset measuring methods are similar in accuracy. It should be noted that this study assumed the crash investigators were all fully trained on the process and thus did not make any mistakes.

As an attempt to establish a clear deformation protocol and help train crash investigators to properly measure crush, Tumbas and Smith published “Measuring Protocol for Quantifying Vehicle Damage from an Energy Basis Point of View” (22). The paper “discusses such a protocol and presents details based on experiences encountered with its evolution and use in certain field accident studies." All methods described in the paper involve physical individual measurements.

In 1989, an alternative was suggested to the individual physical measurements involved in the offset method. A paper was published by Wolf Technical Services, Inc. that introduced the concept of photogrammetry (which "involves the use of multiple two dimensional photographs to create a three-dimensional representation of an object." (23)) and proceeded to show examples of how it could be used in the accident reconstruction process (24).

It wasn't until 2004 when photogrammetry was actually quantitatively examined as a measurement tool for the crush values (23). In this study, the authors used PhotoModeler, a close range photogrammetry software package, and proved that it could be used to determine the C1-C6 values needed for CRASH3 within a reasonable amount of error. This claim was backed up in a 2010 study that compared the accuracy of photogrammetry versus hands-on measurement techniques for the determination of the crush values and actually proved that "the accuracy of the photogrammetry method was found to be slightly greater" (25).

Over the last 25 years, papers have begun to be published about the use of all types of emerging three-dimensional geometric data capture techniques for the application of crash analysis. In most cases, they recognize the need for the new technology to be implemented – for example Tandy et al.'s paper promoting the use of 3D scanners to document vehicle crash scenes and the crashed vehicles (26). But thus far, they have stopped at the describing of vehicle structure after the crash for the calculation of the WinSMASH crush values.

2.3 Computational Models

For the purposes of analyzing a specific vehicle, computational CAD/FEA models can be developed. These models are typically made by vehicle manufacturers, can vary drastically in complexity and are usually only used internally. Others are made for research purposes, like those developed by the National Crash Analysis Center at George Washington University (27). The main issues with these models are that availability and access are limited and the time and cost required to make each one is very significant. Additionally, each model is only valid for the Make, Model, vehicle generation and body type. Thus the use of CAD/FEA models is typically not feasible for most crash analysis.

2.4 New Ways to Improve Accuracy

In Campbell's 1974 paper, he wrote that for the calculation of crash energy and equivalent barrier speed "the limiting factor is the effort expended in determining the vehicle force-deflection characteristic and recording the field vehicle deformation" (9). That message is the primary motivation for this study. This research explores the use of high resolution load cell barrier tests to derive force-deflection curves for small individualized sections of the vehicle's front structure and the use of emerging 3D laser scanning technology to obtain a more complete and accurate recording of the field vehicle deformation. The goal is that if each of the two limiting factors is improved, the resulting calculation of vehicle crash energy will be improved.

2.5 Summary

Current damage based crash reconstruction methods are limited to describing deformation with a maximum of 6 crush values and are relating those to crash energy by assuming a linear force-deflection relationship that is linear across the width of the vehicle. With the emerging technology of three-dimensional measuring techniques and high-resolution load cell barriers to use for the derivation of stiffness, there is a potential area for method accuracy improvement.

3. Framework and Methodology

The purpose of this study is to develop a method for computing motor vehicle crash energy by incorporating emerging three-dimensional data capturing techniques. To achieve this objective, the study was divided into two steps.

The first step of the research focuses on the use of the three-dimensional data capture techniques to develop a detailed characterization of the vehicle deformation. The second step involves the derivation of detailed stiffness coefficients for the impacted region of the vehicle, which are used to calculate the vehicle crash energy.

The research methods used are both qualitative and quantitative with comparisons to existing automotive industry crash analysis standards.

3.1 Three-Dimensional Characterization of Deformation

In order to characterize the deformation of a motor vehicle, the surface geometry of both the undeformed and deformed vehicle must be measured. Once the two sets of measurements are aligned in the same 3D space, then the distance between the deformed region of the crash vehicle and the corresponding region of the undeformed vehicle can be calculated.

3.1.1 Instrumentation

The exterior geometric capture of the deformed case vehicle can be measured using many different techniques and equipment. These techniques range from manual methods that require each point to be taken individually, to bulk methods that record the location of multiple points at once. Depending on the application, different techniques may be selected based on time, cost, equipment availability, etc.

In most cases, with the exception of crash testing, there is no way to obtain a geometric capture of the exact case vehicle before the crash deformation has occurred. As a result, other sources must be used in order to obtain the pre-crash geometric data. If available, CAD/FEM computer models of the vehicle can be used for the comparison. The other option is to use one of the previously described measurement techniques on an exemplar vehicle in which the exterior matches the case vehicle as closely as possible.

For the purpose of this study, a Leica ScanStation C10 scanner (Leica Geosystems - Norcross, Georgia) was used to capture the geometry of the deformed crash vehicles. The Leica C10 is a time-of-flight system that uses a laser to emit a pulse of light and produces a 3D point cloud by measuring the relative position and distance of surfaces to the scanner position(s) (28). The position of the points is determined using the angles of rotation of the scanner when the point was captured. The scanner can rotate a full 360 degrees horizontally and a maximum of 270 degrees (excluding the 90 degrees underneath the scanner).

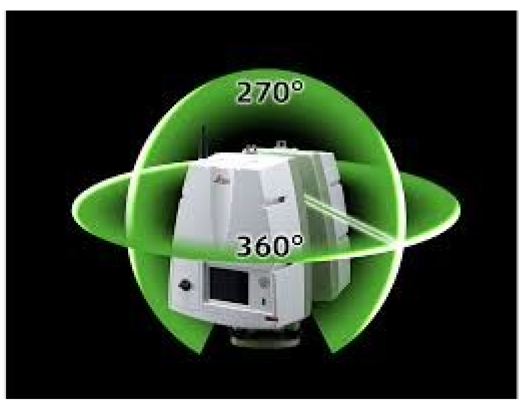


Plate 2 - Leica C10 Rotaition Range (28)

The corresponding distance of each point is determined by measuring the amount of time that the emitted laser takes to hit a surface and return back to the scanner. According to the manufacturer, within a 50 meter range, the accuracy of a single measurement point's position and distance to the scanner location are 6 millimeters and 4 millimeters, respectively

(28). The Leica C10 scanning process also includes the use of geometric targets that remain stationary, allowing the scanner to be used in multiple locations and be able to accurately correlate the 3D point cloud produced at each location to each other.

Additionally, during validation testing, I used 3D geometric data from George Washington University's National Crash Analysis Center (NCAC) (27). NCAC has developed and published a set of Finite Element Models that have been benchmarked with both NCAP and IIHS crash tests for the specific vehicle (27). These are considered as acceptable substitutions in the automotive industry and have been used in a large number of crash analysis research studies (27).

3.1.2 Methodology

The crash energy calculation method proposed in this research is designed to accept geometric data as two sets of three-dimensional points – one for the deformed case vehicle and the other for the appropriate exemplar comparison. The two sets do not need to be measured/obtained in the same manner and thus the two point clouds may have different resolutions, densities and/or point orderings. In most cases, the raw point clouds must be cleaned and/or transformed to make them compatible with each other and allow for the analysis. Any points that do not describe the exterior surface of the vehicle are removed. The point clouds are also transformed such that the two sets have the same reference coordinate system and the vehicles are aligned in the same 3D space.

Once the point clouds have been pre-processed, the deformation of the case vehicle can be measured. The method starts by identifying the side of the case vehicle that was deformed (front, rear, driver's side or passenger side) and direction of the impact in which the deformation occurred. For simplification purposes, case vehicles were only selected for those where the impact direction is approximately perpendicular to a vehicle face and parallel to the bottom of the vehicle, as seen below in Figure 6. The impact plane is then defined using the impact direction as its normal.

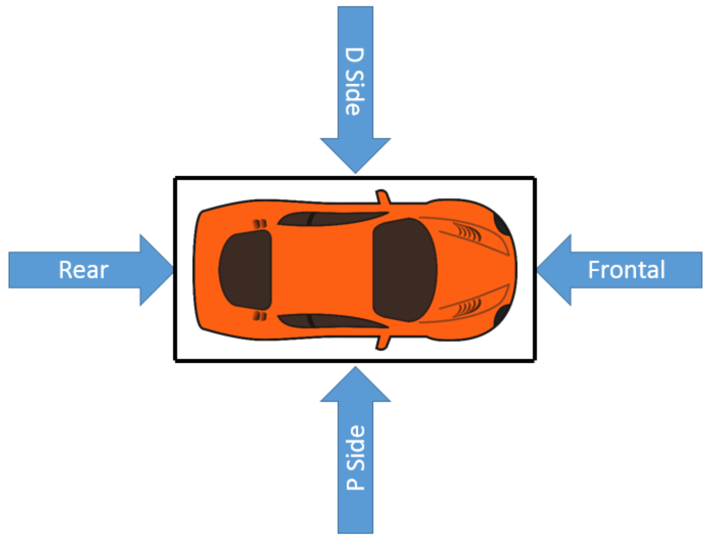


Figure 6 - Impact Directions shown with arrows. Impact Planes shown as lines.

The next step is to define the resolution of the mesh used to characterize the deformation, as seen below in Figure 7. The smaller the mesh regions, the greater the detail of the characterization of deformation. If this result is planned to be used with the force-displacement curves that are derived in the next step, it is recommended that the mesh used is defined by the load cells on the barrier wall. That way the two data sets are already related.

Figure 7 - Mesh Parameters based on Load Cell Barrier Test (28)

The mesh parameters are first applied to the point cloud for the exemplar comparison vehicle. For each mesh cell, a measurement is taken in the impact direction from the impact plane to the exemplar vehicle structure. Once completed, the same mesh parameters are applied to the deformed case vehicle, followed by the equivalent set of measurements.

After the two sets of measurements have been recorded, finding the deformed vehicle's residual crush is as simple as subtracting one from the other:

$$Deformation_{ij} = Exemplar_{ij} - Case_{ij} \qquad \text{Eq. (5)}$$

Where i and j are the rows and columns of the load cells of the impact barrier. A visual representation example of this process done for a vehicle with damage on the driver's side can be found in Appendix 1.

3.1.3 Limitations and Sources of Error

There are two major categories of limitations and sources of error for the development of the three-dimensional characterization of deformation.

The first group of limitations are those involved in the three-dimensional data capture process. As 3D data capture techniques are developed and improved over time, these related limits will continue to decrease. For the development of this method the 3D scanner used was the Leica C10. The identified quality and accuracy issues with this scanner include:

- When the laser hits an edge of a surface, the information that returns to the scanner can be from two different locations for a single pulse of light, which can result in a set of points indicating a false surface.
- When the surface that the laser hits is reflective, the information that returns to the scanner can be distorted.
- The Leica C10 uses a green laser with a wavelength of 532 nanometers. When the surface being scanned is of certain colors (e.g. some reds and blacks), the laser may not return to the scanner or may return with distorted information.
- The data from the different scanner locations is combined using an algorithmic fit to align the targets, but small movements of the scanner and/or targets can increase the error.

In an effort to mitigate the errors resulting from these limitations, the vehicles chosen for use in the study were those that were less likely to have issues (e.g. avoiding shinier vehicles and those of certain colors) and additionally the 3D point clouds were processed using 3DReshaper (Technodigit – Genay, France), a 3D data processing program, to remove many false surfaces and decrease data noise. It should also be noted that baby powder was occasionally used on the vehicles being scanned to compensate for the reflectivity and/or color issues.

The second set of limitations are those specific to certain motor vehicle crash conditions and results. Some of these sources of error can be adjusted for, but others cannot. These issues include:

- Differences between the exterior surfaces of the deformed and exemplar vehicles. Sometimes these differences are due to unique customization, differences in vehicle model year or purchase packages, and/or when a part becomes separated during the crash. In these situations, the method may result in the comparison of the initial position of a point on part A (e.g. front bumper cover) to the final position of a point on part B (e.g. front bumper).
- The method assumes that the deformation of the vehicle is in a uniform direction perpendicular to the deformed side. When the impact angle is not perpendicular, the deformation values will underrepresent the true deformation value by instead showing the perpendicular distance of deformation.

In an effort to mitigate these sources of error, the vehicles chosen for use in the study were those that were less likely to have issues (e.g. matching deformed and exemplar vehicles, and crashes where the impact angle is at or near perpendicular). It should also be noted that when the deformed and exemplar do not match, a factor can be added or subtracted from the deformation calculation for a region where the pre-crash difference is known (e.g. the space between the bumper cover and the bumper on the undeformed vehicle).

An additional source of error is the process of aligning the point clouds of the crash vehicle and exemplar vehicle in the same three-dimensional space. The two sets of points were correlated using sections of the vehicle that remained undeformed and processed in 3DReshaper's "Best Fit" algorithm that shifts and/or rotates the crash vehicle's point cloud (as a single entity) to match the exemplar vehicle.

3.2 Calculation of Crash Energy

In order to calculate the crash energy for a specific case vehicle, the deformation values (derived in the previous step) must be paired with corresponding force/deflection curves. These stiffness relationships are developed using available results from the NHTSA Full Frontal NCAP crash test of that same or an equivalent vehicle. The data used from these tests includes the load cell barrier and vehicle accelerometer signals. From the crash energy, the Equivalent Barrier Speed (EBS) can also be calculated.

3.2.1 Data Sources

Since 1979, NHTSA's New Car Assessment Program has conducted crash tests of new vehicles to determine the vehicle safety ratings (29). Each type of vehicle undergoes a series of crash test configurations including multiple types of frontal, side and rollover. For the purposes of this research, the crash configuration type was limited to frontal crashes and thus stiffness values were only derived for that section of the vehicle.

Of the frontal crash test types, the one used to calculate the stiffness values is the full frontal test. For this test, the vehicle is launched into a stationary non-deformable flat barrier at 56 km/h (35 mph) with a 12 o'clock direction of force and 100 percent overlap. To track the vehicle's movement, the vehicle is instrumented with over a dozen accelerometers placed in multiple locations and multiple high-speed cameras are set up to record the crash events.

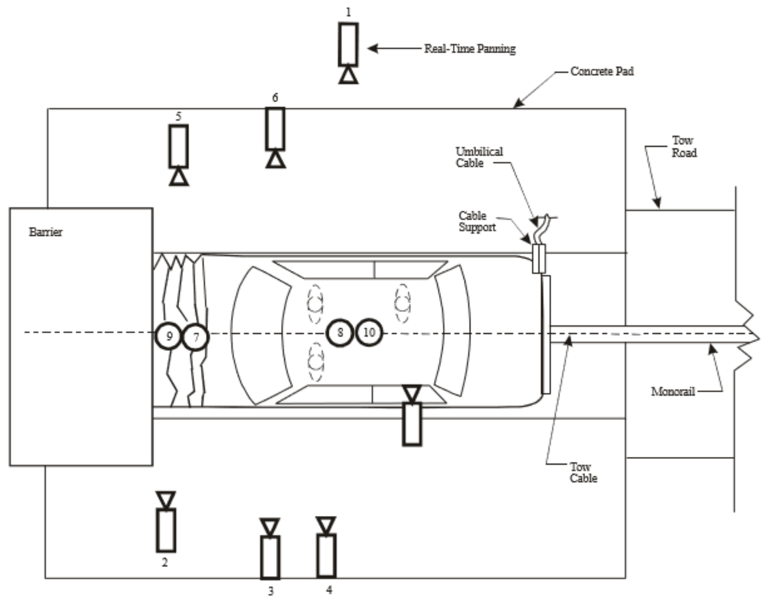


Figure 8 – NHTSA Full Frontal NCAP Test Configuration (20)

To calculate the collision crash energy, the barrier is equipped with load cell barriers that measure and record the amount of force applied to the wall over time. The original barriers included 36 load cells arranged in the configuration seen below.

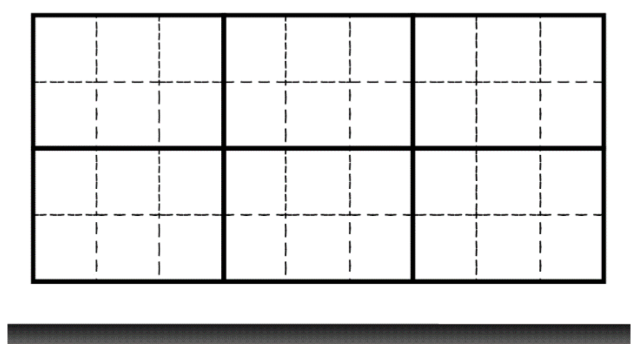


Figure 9 - Low Resolution Load Cell Barrier Configuration (28)

In 2010, NHTSA began to conduct some of the Full Frontal NCAP tests using high resolution load cell barriers. These barriers are equipped with between 128 and 134 smaller load cells that are able to provide much more detailed force distribution values across both the width and height of the vehicle front. The load cells are arranged in an 8 by 16 grid with additional cells sometimes placed in the middle of the top row, as seen in Figure 10.

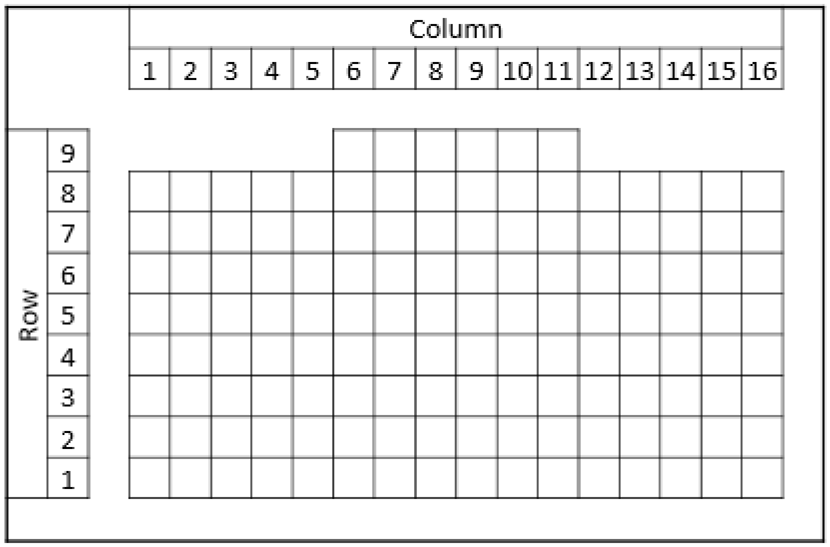


Figure 10 - High Resolution Load Cell Barrier Configuration

After each crash test has been completed, processed and reviewed, it is uploaded to NHTSA's online Vehicle Crash Test Database. Each test in the database includes a detailed crash test report, all available pictures and video, and downloadable raw signal data for all the accelerometers and load cells used in the test. This dataset is publically available and can be found on NHTSA's website (29).

3.2.2 Methodology

For the derivation of the vehicle frontal stiffness values in this study, signal data is needed for the forces on the barrier and the movement of the vehicle during the crash. The force data from the flat non-deformable barrier is downloaded as a set of force versus time curves, which includes one for each individual load cell. In order to relate these forces to specific sections of the vehicle deformation (from the previous step), it is important to document the load cell location for each curve. Figure 11 shows an example plot of the forces on each of the individual load cells (on the impact barrier) over time during the crash. The data was taken from one of NHTSA's Full Frontal NCAP tests (20).

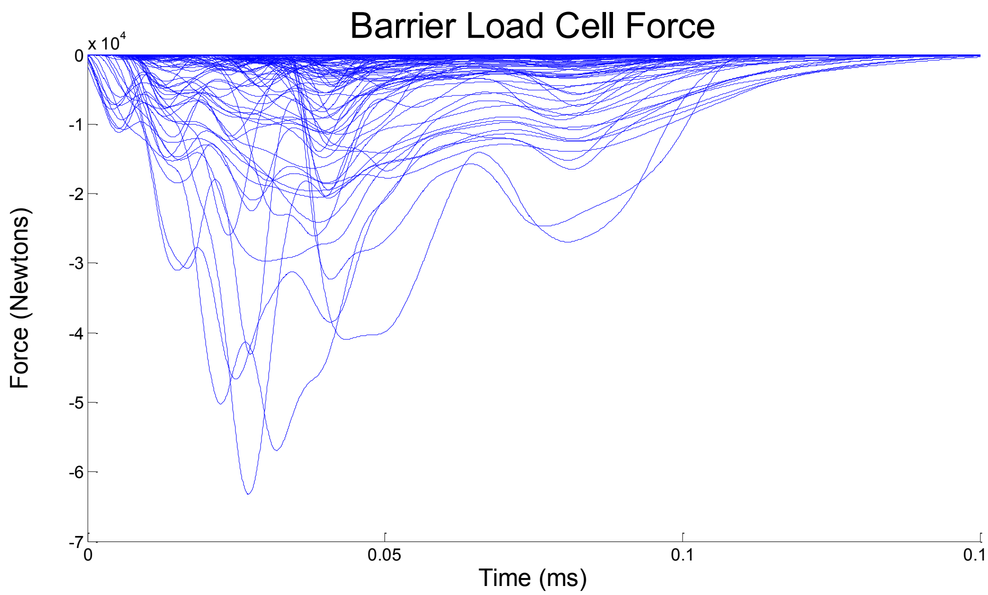


Figure 11 - Load Cell Barrier Forces versus Time (NHTSA Test #5143 (20))

To describe the vehicle movement, acceleration data is downloaded from a longitudinal-direction (along the length of the vehicle) accelerometer that is attached to the main structure and far enough back that it is behind the deformed region. The accelerometer placed at the vehicle's center-of-gravity will typically yield the best results but, if unavailable, data from the vehicle's rear deck will also work.

Using basic kinematic relationships, the acceleration data is translated into the vehicle velocity and then to the vehicle's displacement, as seen below in Equations (6, 7) and Figure 12. This example data was taken from the same NHTSA crash test as Figure 11. Time is adjusted such that time zero is the point at which the vehicle makes contact with the barrier wall, thus the initial position is zero. The data is valid until the point when the vehicle separates from the barrier, indicated by t_S. The vehicle impact velocity at that time is taken from the vehicle's equipped event data recorder (EDR).

$$Velocity(t) = \int_{t_0}^{t_s} Acceleration(t) * dt + Impact\ Velocity \qquad \text{Eq. (6)}$$

$$Position(t) = \int_{t_0}^{t_s} Velocity(t) * dt \qquad \text{Eq. (7)}$$

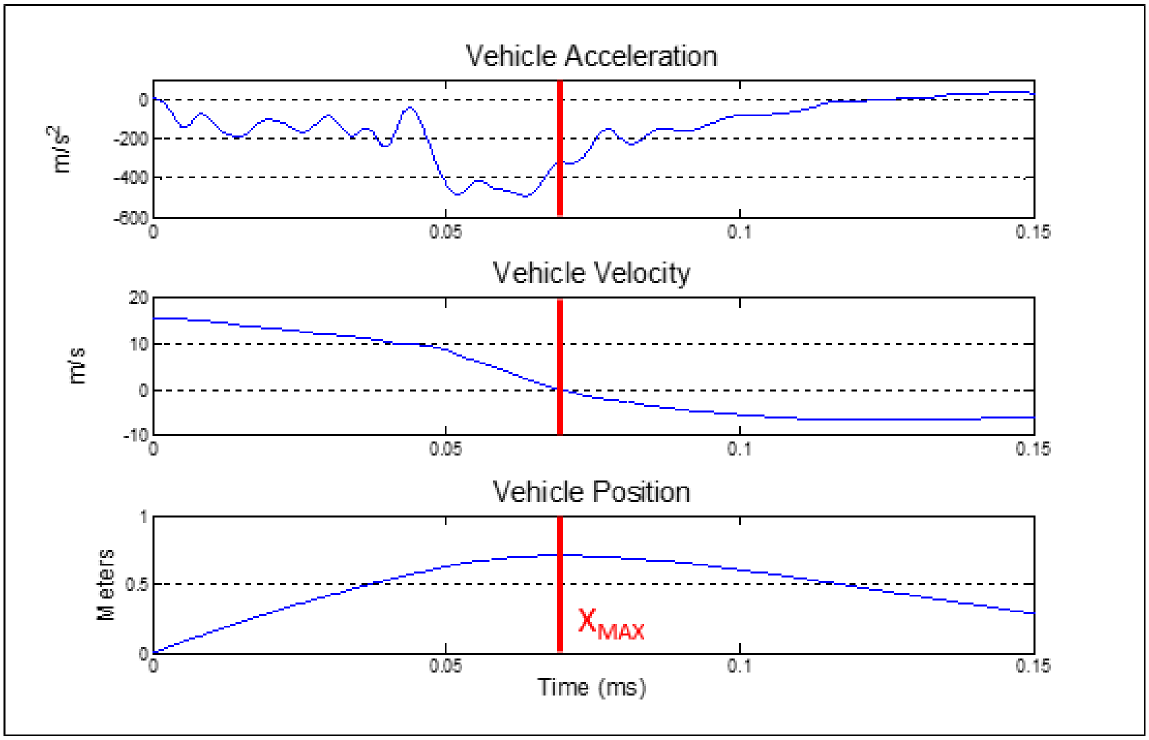


Figure 12 - Example Curves of Vehicle Acceleration, Velocity and Position over Time (NHTSA Test #5143 (20))

For a physical understanding of these values, the curves above (Figure 12) are used to describe the series of events that occur during the crash. The vehicle velocity is considered positive as the vehicle continues to move towards the barrier wall. Time t_0 is defined as when the vehicle first makes contact with the barrier. At the point where velocity equals zero, the vehicle has reached its maximum dynamic crush – defined as X_{MAX} for the end of the energy absorption period. Beyond this point, the vehicle front structure undergoes elastic recovery until it has reached the final residual crush, X_{RES}, (which is the deformation measured after the crash). During recovery, the vehicle's structure pushes back against the wall and causes the vehicle velocity to go negative. The point of separation is defined when the sum of the forces on the load cell barrier equals zero.

The detailed stiffness values can now be defined by relating the force curves to the vehicle position curve – resulting in force-displacement relations. At this point, all the necessary data is available to calculate the vehicle crash energy.

To calculate the crush energy, you start with regards to the residual crush from the NCAP crash test by determining the amount of work done on the vehicle by the barrier wall from the time of impact to the time of maximum dynamic crush:

$$WORK_1 = \int_{X_E}^{X_{RES}} Force_{i,j} * dX \qquad \text{Eq. (8)}$$

Where X_E is the measurement of the exemplar location for a given region – this is because a car front is not completely flat. Thus not all parts of the structure engage the barrier at the same time. $Force_{i,j}$ is the force on each individual transducer.

Then one can determine the amount of work done by the vehicle structure to the wall during the time of elastic recovery, as seen in Eq. (9).

$$WORK_2 = \int_{X_{RES}}^{X_{MAX}} Force_{i,j} * dX \qquad \text{Eq. (9)}$$

An elastic ratio is necessary to compensate for the fact that we are measuring residual crush instead of maximum dynamic crush. During the time of the accident, the load cell barrier records the forces as a result of both the elastic and plastic deformations. Yet, the measurements of crush done post-crash only represent the non-reversible plastic deformation. Thus the elastic ratio represents the addition of the energy absorbed through elastic deformation similar to the coefficient of restitution.

$$Elastic\ Ratio = {}^{(WORK_1 + WORK_2)}\!\big/_{(WORK_1)} \qquad \text{Eq. (10)}$$

These values of work are per individual load cell and thus they must be summed across the entire face of the vehicle.

$$\Delta KE = \sum_{i=1}^{rows} \sum_{j=1}^{cols} WORK_1 * Elastic\ Ratio \qquad \text{Eq. (11)}$$

And lastly, Equivalent Barrier Speed is calculated using:

$$EBS = \sqrt{\frac{2*\Delta KE}{v_{mass}}} \qquad \text{Eq. (12)}$$

The set of equations must then be repeated with regards to the residual crush for the case vehicle.

$$WORK_1 = \int_{X_E}^{X_{RES}} Force * dX \qquad \text{Eq. (13)}$$

The Elastic Ratio from the NCAP based calculation is used to determine the crash energy of the case vehicle as follows:

$$\Delta KE = \sum_{i=1}^{rows} \sum_{j=1}^{cols} WORK_1 * Elastic\ Ratio \qquad \text{Eq. (14)}$$

And finally, the EBS is calculated for the case vehicle.

$$EBS = \sqrt{\frac{2*\Delta KE}{v_{mass}}} \qquad \text{Eq. (15)}$$

3.2.3 Limitations and Sources of Error

The limitations and sources of error for the crush energy calculation fall into two main categories. The first are those where the crash test dynamics aren't exactly as modeled. Those include:

- When deformation plane isn't exactly perpendicular to the surface
- Bending and other interconnected forces
- During a frontal vehicle crash, the vehicle will pitch down a bit during impact which may cause a shift in the load cells relative to the vehicle front structure.

The second category of limitations and error are based on the method of calculation. They include:

- Effects of significantly different speeds on the Elastic Ratio
- Case where the vehicle's deformation exceeds the maximum dynamic crush in the crash test.

3.3 Summary

This chapter described the method and framework that were used to characterize the vehicle deformation, derive detailed stiffness values, and calculate crash energy and equivalent barrier speed.

4. Procedure and Data Analysis

4.1 Three-Dimensional Characterization of Deformation

This section shows the complete procedure that is undertaken to obtain the 3D geometric data for both the deformed and exemplar vehicles and the process that the data undergoes to develop the 3D characterization of deformation. During the development and testing of the process and methodology, I scanned about two dozen vehicles.

4.1.1 Data Sources

Through an agreement with the BMW Accident Research Project, I was given access to BMW vehicles that had been deformed in real-world crashes across the country. In most cases, when the vehicle is considered totaled, it is removed from its original accident scene and eventually makes its way to a large tow-yard. When the crashed vehicle fit within the criteria of this study, I travelled to the tow-yard and was given permission to scan it (using the Leica C10).

I was also given access to BMW dealerships where I was able to create a library of BMW exemplars by scanning undeformed vehicles. These exemplars included the closest available match to the deformed vehicles based on model, model year and vehicle exterior configuration. Additionally, a proof of concept was done to use a BMW manufacturer's CAD file of the vehicle's exterior surface as the exemplar vehicle.

Most of the development of the three-dimensional characterization of deformation part of this study was done using BMW vehicle data. The deformed vehicles were all real world crashes and the corresponding exemplars used were from the dealerships. In addition to the BMW vehicles, 3D geometric data was also derived from two of NCAC's Finite Element Models: 2001 Ford Taurus and 2006 Ford F250 (27). These vehicles were chosen because they have both been tested by NHTSA in the Full Frontal NCAP configuration (with a high resolution load cell barrier) and by IIHS in the Moderate Overlap configuration (27).

4.1.2 Data Analysis

The process starts with the selection of a case vehicle of interest. As mentioned earlier, case vehicles were limited to those that were involved in crash configurations where the primary direction of force was either 12, 3, 6 or 9 o'clock. Additionally, deformed vehicles where an excessive amount of sheet metal was removed, were avoided unless the case had special significance.

Once the case vehicle was selected, both the case vehicle and the exemplar vehicle were scanned. For each vehicle, the scanner is set up in multiple locations around the vehicle. Targets were placed on and around the vehicles that were used to triangulate the different scanner locations. Plate 3 below shows an example of what the scanner records at an individual scan location – in this case the scanner was placed in front of the vehicle.

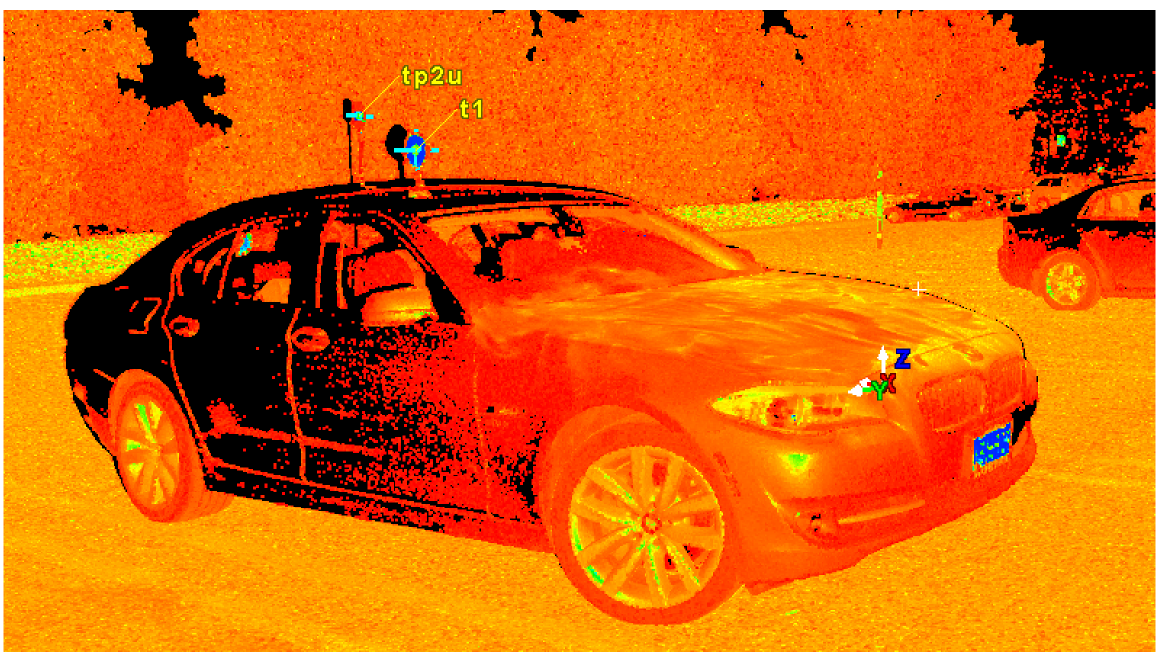


Plate 3 - Data Capture in the Field (View from a single ScanWorld) – BMW Example Data

Once the scanner has been placed at sufficient locations around the vehicle to capture the complete exterior surface, the on-scene work is done. The next step is to load the raw scan data into Leica's scanner software, Cyclone (Leica Geosystems – Heerbrugg, Switzerland). Within this program, the scans from each location are combined through a process of best-fit triangulation. For two different point clouds to be combined, they must have at least 3 common targets. Plate 4 shows what the data looks like once multiple scan locations have been combined.

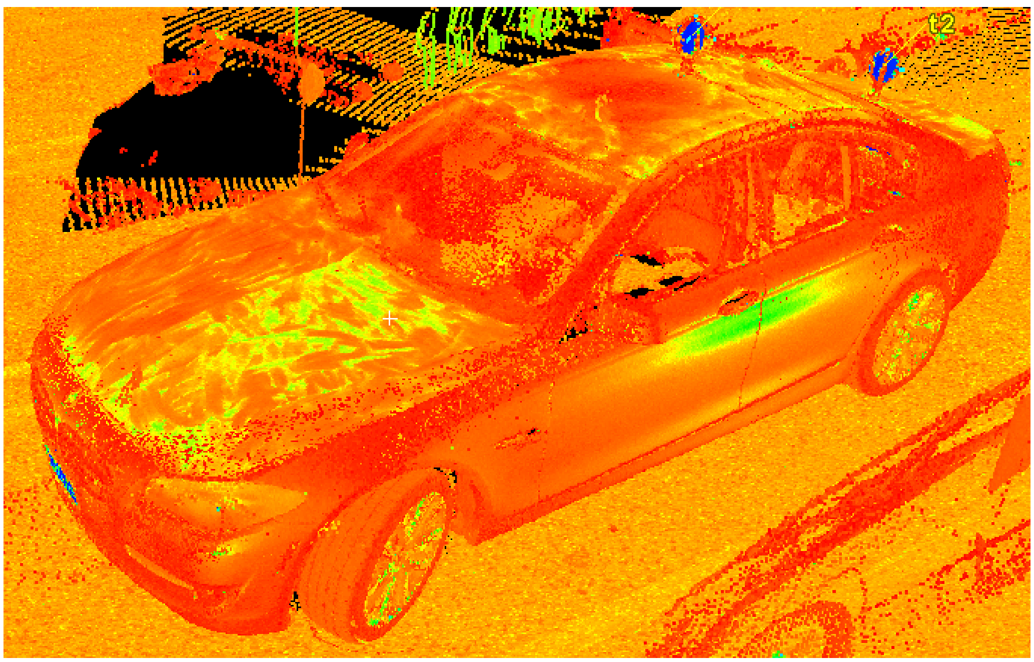


Plate 4 - Registration of ScanWorlds – BMW Example Data

After all the scan locations have been combined, the data is exported out of Cyclone as a single file (for each case vehicle and exemplar vehicle) and loaded into 3DReshaper , a scanner program better suited for data cleanup. During the cleanup process, all non-vehicle points are removed, as seen in Plate 5. The next step is to remove the vehicle interior such that the point cloud remaining is just a shell representing the exterior of the vehicle, as seen in Plate 6.

Lastly, the case and deformed vehicle shells are moved into the same 3D space using 3DReshapers best-fit algorithm. The program allows selecting undeformed points on the case vehicle and the corresponding point on the exemplar vehicle. Once enough common points are selected, the vehicle shells will align themselves. Plate 7 shows a visual representation of the case and exemplar vehicles in the same 3D space. At this point, the pre-processing is complete. The two point cloud files can now be loaded into MATLAB and analyzed by a script that was developed for purposes of this study.

Plate 5 - Exemplar Scan with all non-vehicle points removed – BMW Example Data

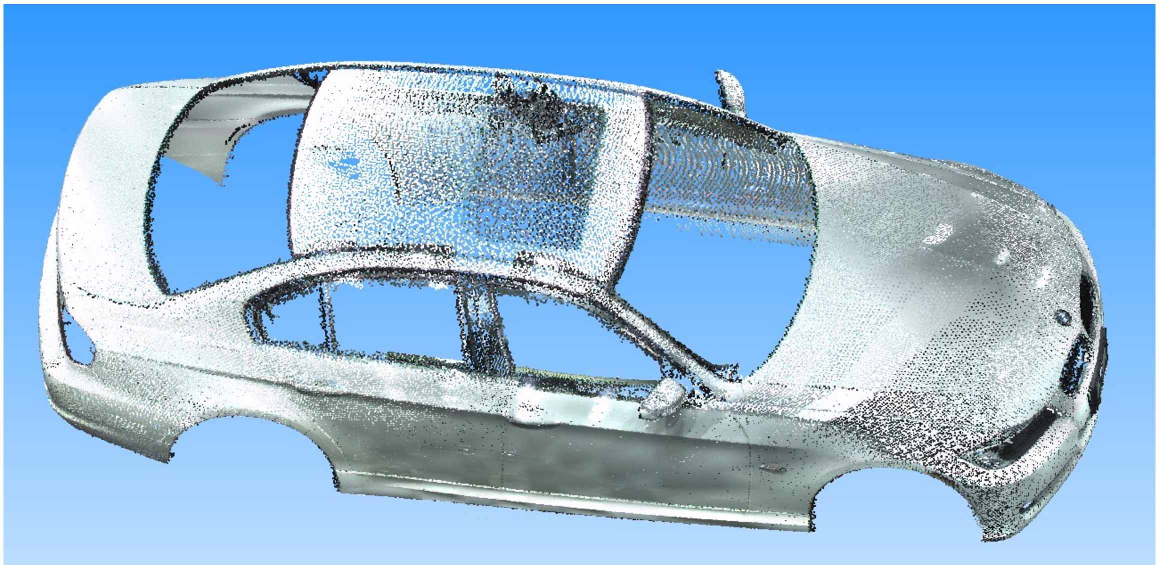


Plate 6 - Exemplar Data cleaned to vehicle exterior shell– BMW Example Data

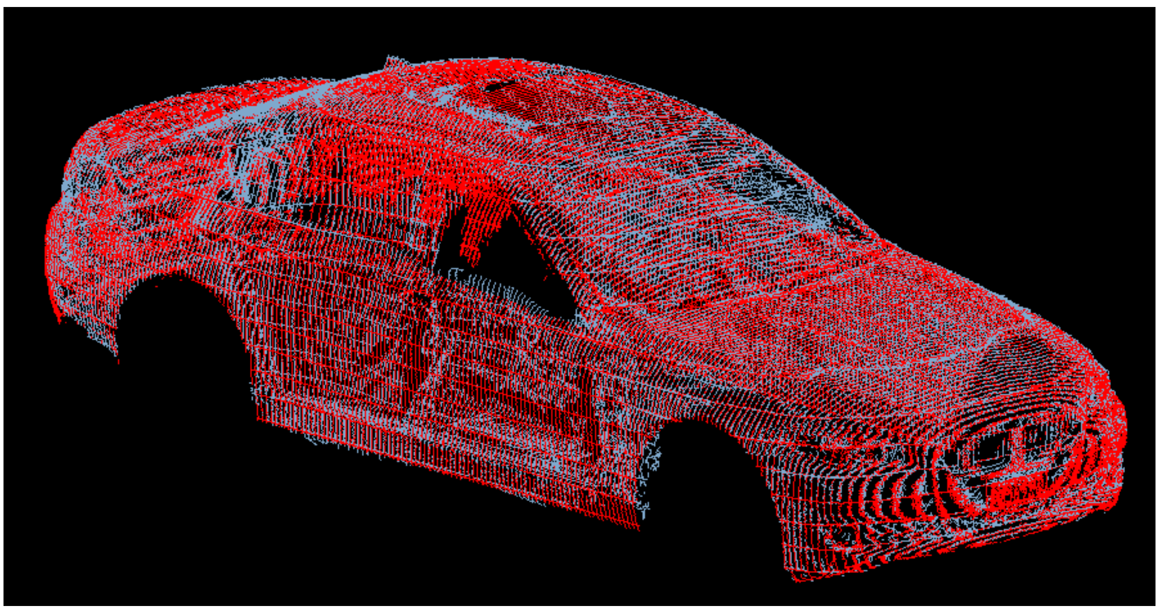


Plate 7 - Case and Deformed Vehicle Shells have been aligned into the same 3D space – BMW Example Data

In addition to the case and exemplar vehicle point clouds, the MATLAB script requires the user to identify the deformed side and to describe the mesh that will be implemented. When the intent is to determine crash energy, it is recommended that the barrier load cell locations are used.

The MATLAB script starts processing the point cloud by cutting the vehicle in half (and leaving the deformed side). This drastically speeds up the script run time and also prevents points from the other side to be measured. The script then applies the defined mesh by sorting all of the remaining points into a 2D version of the mesh grid (based on the impact plane, with the third dimension being the one that goes into the vehicle). Next, it looks within each mesh grid and finds the points closest to the impact plane. The measured distance for each grid is the average distance of those first set of points.

After both the case and exemplar point clouds have been measured, the distance between them is calculated. These calculated values of displacements are stored in a matrix with dimensions corresponding to the applied mesh.

4.2 Crash Energy Calculation

This section shows the complete validation procedure that is taken to calculate the vehicle crush energy and equivalent barrier speeds based on stiffness values derived from crash test data.

4.2.1 Data Sources

For the development of this method of crash energy calculation, it is necessary to have detailed deformation data for the exact vehicle that was used in the NHTSA NCAP Full Frontal Crash Test. This is needed in order to be able to determine the elastic ratio (the ratio between the elastic and plastic deformation) for the vehicle. Unfortunately, NHTSA's published crash test reports only describe the vehicle deformation with the crush values C1-C6 which is not sufficient for this method. Thus I filed a request to scan one (or more) of the actual NHTSA crash test vehicles, but unfortunately, that request was declined.

As a solution, I instead used 3D geometric data from George Washington University's National Crash Analysis Center (NCAC) (27). The specific FE vehicle models chosen were the 2001 Ford Taurus and the 2006 Ford F250 (27). They were processed with the accelerometer and load cell data from their corresponding NHTSA Full Frontal NCAP tests: NHTSA test 5143 – Ford Taurus (20) and NHTSA test 5820 – Ford F250 (30).

4.2.2 Data Analysis

Thus, for the procedure and testing of the study, I completed the entire method (both the 3D characterization of deformation and the crash energy calculation) using a 2001 Ford Taurus as my subject vehicle. It was run in the NHTSA Full Frontal Crash configuration as NHTSA Test Number 5143 (20). As part of the NCAC's model development, the vehicle was simulated in the NHTSA NCAP Full Frontal Crash configuration and verified to match the results of the actual physical test, which provides me the necessary geometric data for the force-deflection relationship calculation. Additionally, since the geometric data used came from the NCAC, any error found in the 3D scanning process was completely avoided.

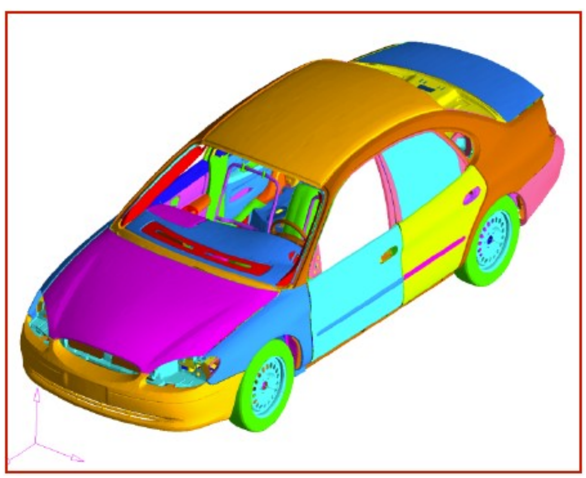


Figure 13 - NCAC Finite Element Model of 2001 Ford Taurus V3 (27)

Once the force-deflection curves were derived for the Ford Taurus, the validation procedure chosen was to see how the method preforms when calculating the crash energy of the vehicle having undergone the IIHS Moderate 40% Overlap crash test configuration, which is “conducted at 64.4 ± 1 km/h and 40 ± 1 percent overlap” (31). This test configuration serves as a good example of a crash configuration in which the WinSMASH code’s calculated delta-V has a high error. Much of this error results from the assumption of uniform linear stiffness across the deformed region. Thus a more descriptive set of crush measurements and non-linear force-deflection values should help to increase the accuracy.

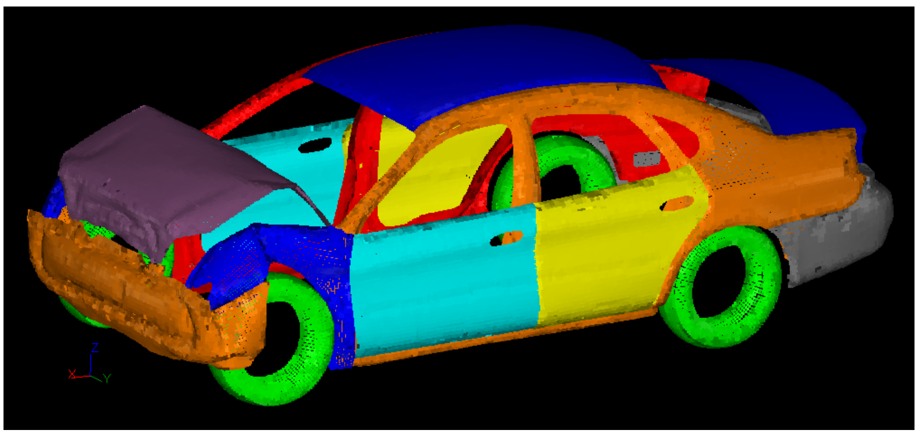


Plate 8 - NCAC Model after NCAP Full Frontal Crash –NCAC Taurus Model

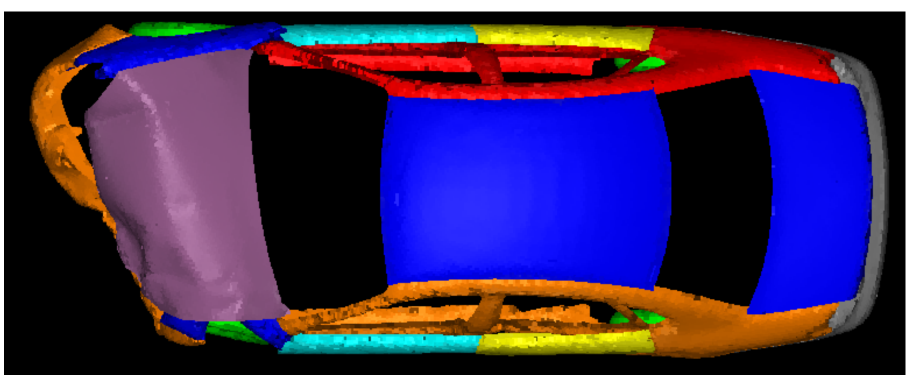


Plate 9 - NCAC Model after IIHS 40% Overlap Crash –NCAC Taurus Model

4.3 Summary

The first half of this chapter give details to the procedure executed in order to characterize the vehicle deformation. The second half establishes a validation procedure that allows the method of calculating crash energy to be independently studied by using geometric data from the NCAC FEM Model of the Ford Taurus.

5. Results

The results shown in this chapter are based on the analysis of a fourth generation (model years 2000-2007) Ford Taurus sedan. The geometric data for the vehicle is derived from the corresponding NCAC Finite Element Model (for the exemplar vehicle, the vehicle damaged under Full Frontal NCAP configuration and the vehicle damaged under IIHS Moderate Overlap configuration) (27). The accelerometer and load cell data used to develop the vehicle's force-deflection curves come from NHTSA's Full Frontal NCAP test number 5143 that was run by TRC (20). This analysis is used in the validation testing of the proposed method.

5.1 Three-Dimensional Characterization of Deformation

Plate 10 and Plate 11 show a graphical representation of the crush measurements recorded using the research method. In both images, the blue lines represent the exemplar vehicles and the red/green lines represent the deformed case vehicles. Plate 10 shows the crush measurements taken at different heights across the vehicle and Plate 11 shows those taken across the width of the vehicle.

For the purposes of the calculation of crash energy and delta-V, the crush measurements are recorded in a matrix with the dimensions matching those of the physical load cell barrier (9 by 16).

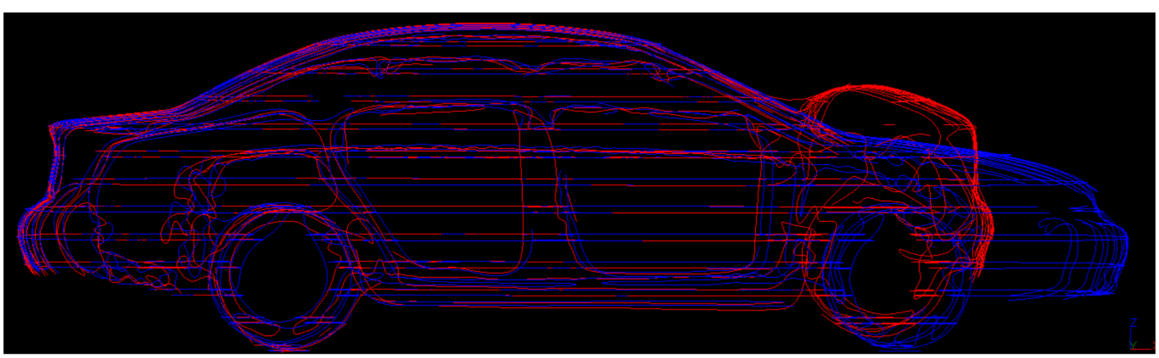


Plate 10 - NHTSA Frontal NCAP Test (Exemplar vs Deformed) –NCAC Taurus Model

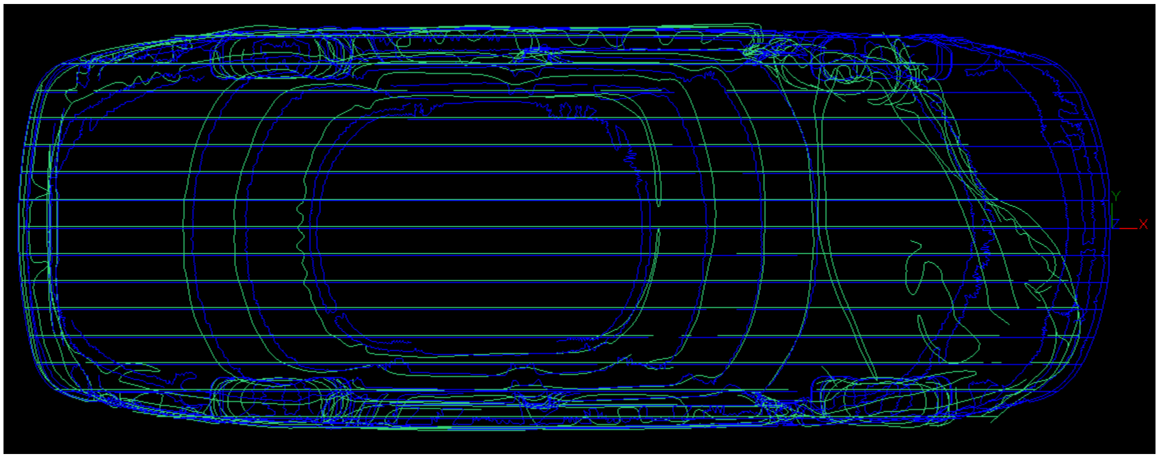


Plate 11 - IIHS 40% Overlap Test (Exemplar vs Deformed) –NCAC Taurus Model

As can be seen by these images, the greater number of crush measurements provides a much more descriptive and useful deformation pattern.

5.2 Crash Energy Calculation

For each vehicle, the load cell forces and the accelerometers from the NHTSA NCAP Full Frontal Crash Test are used to develop that vehicle's specific force-deflection curves and the corresponding elastic ratio. Once that has been derived, the model can be run to calculate the crash energy of that vehicle for any frontal crash configuration. As described in the procedure, the Ford Taurus model was processed in both the NHTSA NCAP Full Frontal configuration, to set the baseline values, and the IIHS Moderate Overlap Crash configuration, as a validation test.

5.2.1 NHTSA NCAP Full Frontal Crash Configuration

The first set of results show the validation of the baseline data, the values used to determine crash energy. Figure 14 shows that CRASH3 baseline data (based on the vehicle event data recorder) for 2004 Ford Taurus is a Test EBS of 55.9 km/h. This value matches the EBS (non-restitution) value produced by the research method, seen in Table 1.

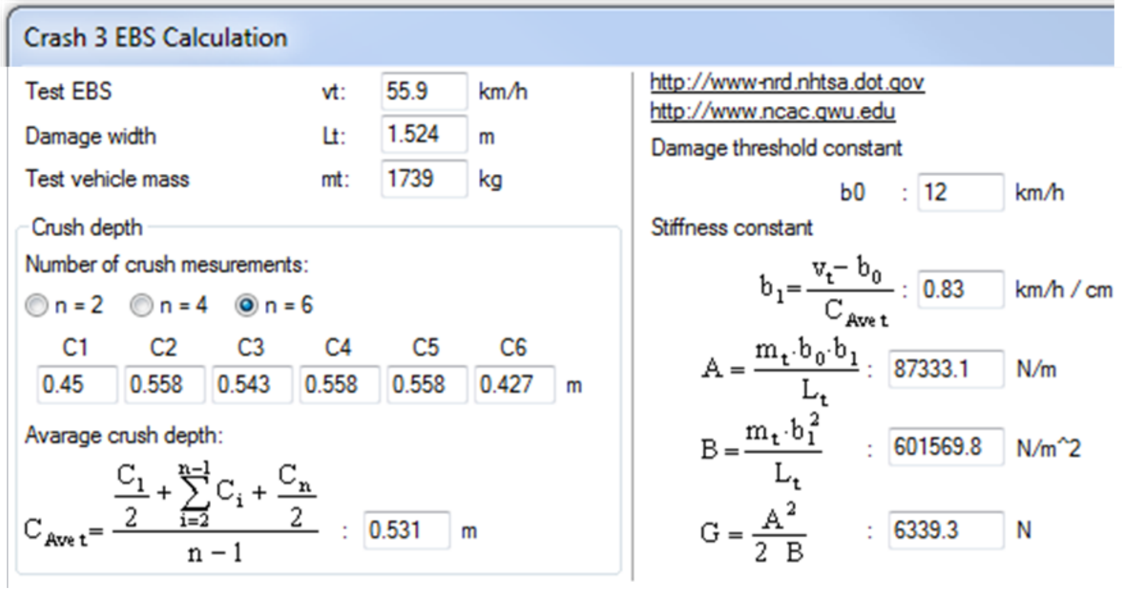


Figure 14 - Comparison to CRASH3 for Ford Taurus (Produced using PC-Crash's CRASH3 tool)

Developed Method Results	
Equivalent Barrier Speed (EBS)	15.5432 m/s
	55.9556 km/h
	34.7693 mph
delta-V	18.6519 m/s
	67.1467 km/h
	41.7231 mph

Table 1 - Results from NCAP Full Frontal Test for Ford Taurus

5.2.2 IIHS 40% Overlap Crash Configuration

This set of results shows the application of both the CRASH3 and proposed research method for the calculation of EBS (non-restitution delta-V) on the IIHS Moderate Overlap crash test configuration. Figure 15 shows the input of the crush measurements into the CRASH3 program. In this case, 11 crush measurements (C1-C11) were recorded by the investigators who conducted the crash. Figure 16 shows CRASH3's calculated values based on those crush measurements.

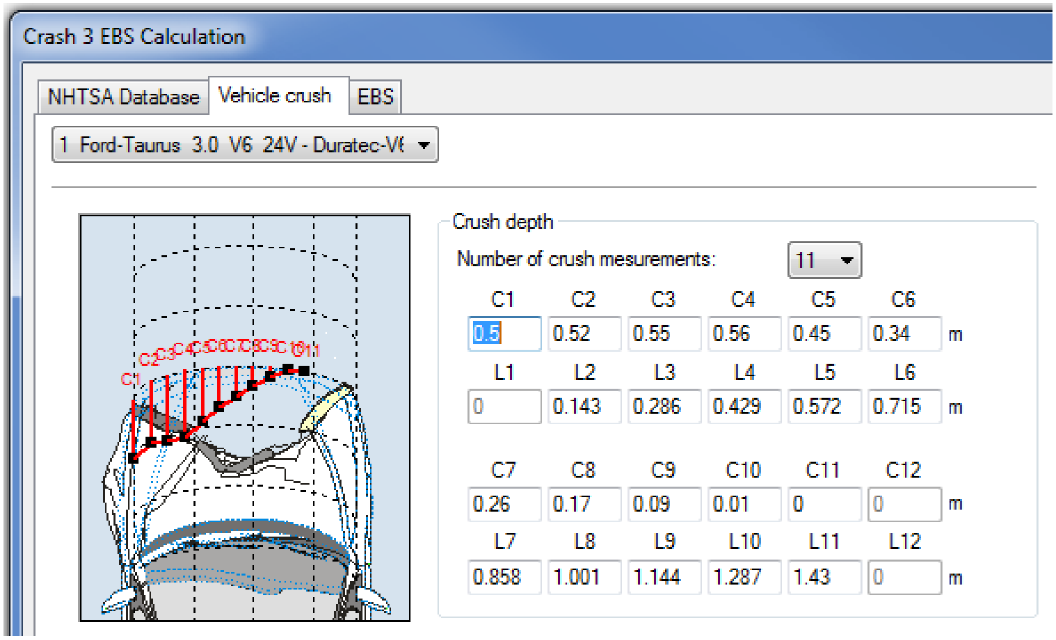


Figure 15 - Defining Vehicle Crush using CRASH3 for Ford Taurus (Produced using PC-Crash's CRASH3 tool)

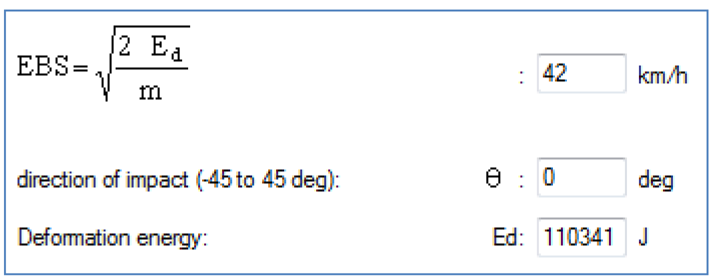


Figure 16 - CRASH3 Predicted Values for Ford Taurus (Produced using PC-Crash's CRASH3 tool)

Lastly, Table 2 shows the delta-V values calculated using the proposed research method. The calculated EBS value is expected to be a bit lower because the deformation in the Moderate Overlap Crash configuration exceeds that in the NCAP Crash configuration. The objective is to prove that the EBS values are in the same general range.

Developed Method Results	
Equivalent Barrier Speed (EBS)	10.6679 m/s
	38.4043 km/h
	23.8634 mph
delta-V	12.8014 m/s
	46.0852 km/h
	28.636 mph

Table 2 - Results from the IIHS 40% Overlap Test for Ford Taurus

6. Conclusions and Recommendations

6.1 Conclusions

Although only limited validation of the model was done, the preliminary results are quite promising. The method presented shows that the more detailed characterization of deformation can be combined with high-resolution load cell barrier tests to provide accurate results and potentially fix some of the deformation based calculation errors seen when using WinSMASH. An addition to the crash energy calculation part of the method needs to be made to allow for the deformation values beyond the maximum dynamic crush seen in the NCAP crash test.

6.2 Recommendations

I believe that 3D laser scanning has come a long way in the last 20 years but that the process of using the data still needs more development. The amount of pre-processing time that is currently required, at least based on the scanner that I used, is quite excessive. Automated methods need to be derived to make the scanner more cost effective.

It is clear that more testing needs to be done on the method for validation purposes including more extensive comparison to other currently used methods.

6.3 Summary

This section discusses the conclusions and recommendations based on the presented method development and the validation results. Based on preliminary results, it has demonstrated that the method has merit.

References

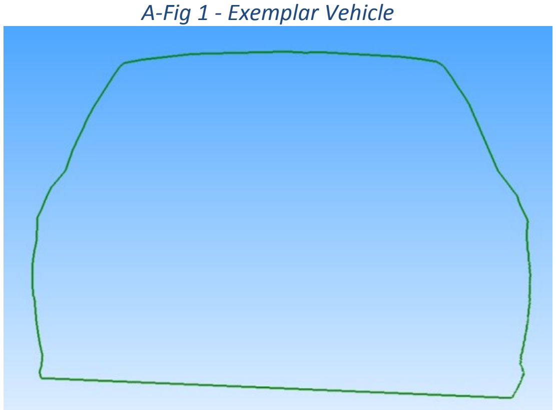
List of Appendices

Appendix 1

The following set of images shows the process of how the deformation values are calculated for one cross-section of a vehicle with driver's side deformation.

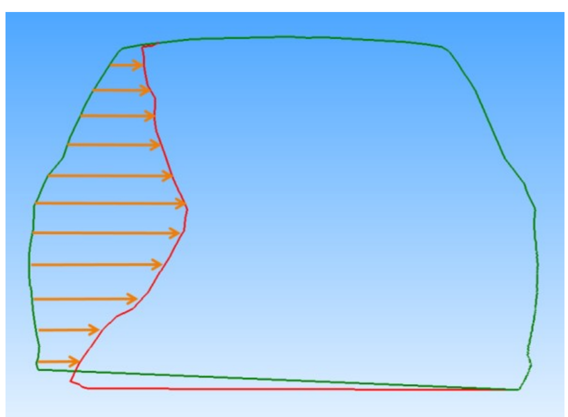
A-Fig 1 - Exemplar Vehicle

A-Fig 3- Deformed Vehicle



A-Fig 2 - Cross Section of Exemplar Vehicle

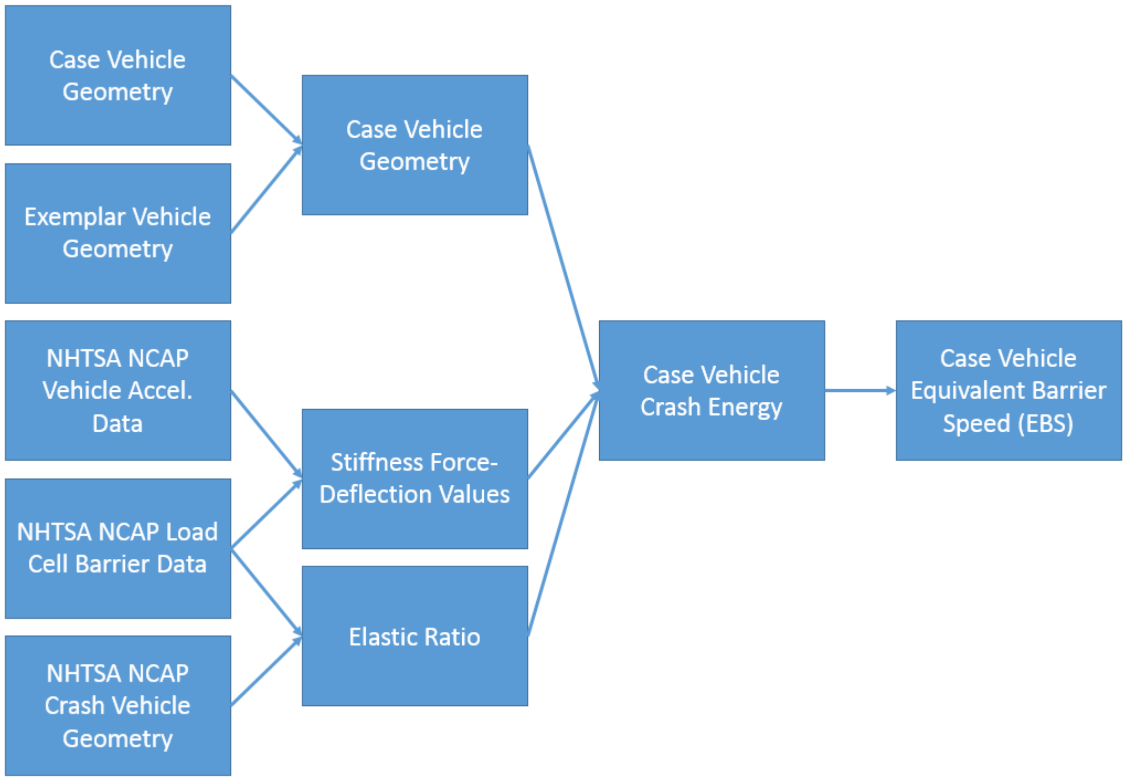
A-Fig 4 - Cross Section of Deformed Vehicle



A-Fig 5 - Arrows indicate measurement of deformation

Appendix 2

The following is a visualization of the inputs and outputs used in the developed method.



A-Fig 6 – Developed Model Inputs and Outputs

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Curriculum Vita

Brandon Leibowitz was born in Miami, Florida. In May 2011, he received his degree in Bachelor of Science in Mechanical Engineering at Pennsylvania State University, University Park, Pennsylvania. He then started his M.S. program at Johns Hopkins University, Baltimore, MD. He received his Master of Science in Mechanical Engineering in Fall 2014.

From June 2010 to October 2013, Mr. Leibowitz worked as a Mechanical Engineer Research Associate for Impact Research, LLC in Baltimore, Maryland, where he gained experience in the field of automotive safety, driver behavior and injury biomechanics. During that time, he participated in numerous studies involving evaluation of occupant protection and crashworthiness countermeasures, evaluations of second generation and advanced airbag systems, and evaluations of safety technology for elderly occupants. He also conducted engineering analysis and studies of causation factors of vehicle crashes as member of the BMW Accident Research Program and provided recommendations to improve safety of BMW vehicles as a result of these findings. Mr. Leibowitz managed IR's qualitative and quantitative analysis of consumer complaint data in an effort to better understand and predict vehicle defects. He also developed and conducted the described research study as a part of Impact Research's accident research.

Mr. Leibowitz is currently working as a Product Development Engineer for Ford Motor Company in Dearborn, Michigan.